

A massive white dwarf member of the Coma Berenices Open Cluster

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ABSTRACT

We report the identification, from a photometric, astrometric and spectroscopic study, of a massive white dwarf member of the nearby, approximately solar metallicity, Coma Berenices open star cluster (Melotte 111). We find the optical to near-IR energy distribution of WD1216+260 to be entirely consistent with that of an isolated DA and determine the effective temperature and surface gravity of this object to be $T_{\text{eff}}=15739^{+197}_{-196}\text{K}$ and $\log g=8.46^{+0.03}_{-0.02}$. We set tight limits on the mass of a putative cool companion, $M \gtrsim 0.036M_{\odot}$ (spatially unresolved) and $M \gtrsim 0.034M_{\odot}$, (spatially resolved and $a \lesssim 2500\text{AU}$). Based on the predictions of CO core, thick-H layer evolutionary models we determine the mass and cooling time of WD1216+260 to be $M_{\text{WD}}=0.90 \pm 0.04M_{\odot}$ and $\tau_{\text{cool}}=363^{+46}_{-41}\text{Myrs}$ respectively. For an adopted cluster age of $\tau=500 \pm 100\text{Myrs}$ we infer the mass of its progenitor star to be $M_{\text{init}}=4.77^{+5.37}_{-0.97}M_{\odot}$. We briefly discuss this result in the context of the form of the stellar initial mass-final mass relation.

Key words: stars: white dwarfs; galaxy: open clusters and associations: Melotte 111, Coma Berenices open cluster

1 INTRODUCTION

Galactic open star clusters have for decades been regarded as key entities with which to address important issues in stellar and galactic astrophysics e.g the form of the stellar initial mass function, the evolution of stellar angular momentum and the form of the initial mass-final mass relation. This is because fundamental stellar parameters such as age and composition can be more stringently constrained through studying a co-eval ensemble of objects at essentially the same distance (e.g. Meynet, Mermilliod & Maeder 1993).

Melotte 111 (Coma Berenices cluster, $\text{RA}=12^{\text{h}}22^{\text{m}}$, $\text{DEC}=+26^{\circ}$, J2000.0) is the second closest open star cluster to the Sun. It appears to be marginally younger than the Hyades or Praesepe, with most recent age estimates lying in the range $\tau=400\text{--}600\text{Myrs}$ (e.g. $\tau \approx 450\text{Myrs}$, Bounatiro & Arimoto 1992; $\tau \approx 500\text{Myrs}$, Odenkirchen et al. 2001; $\tau \approx 600\text{Myrs}$, Kharchenko et al. 2005). Cayrel de Strobel (1990) has determined $[\text{Fe}/\text{H}]=-0.065 \pm 0.021$ from a high resolution spectroscopic study of a sample of eight F-, G- and K- type members. A similar but independent investigation of fourteen F and G dwarf associates has concluded that $[\text{Fe}/\text{H}]=-0.052 \pm 0.047$ (Friel & Boesgaard 1992). More recently, Gebran, Monier & Richardo (2008), have determined $[\text{Fe}/\text{H}]=0.07 \pm 0.09$ through the high resolution spectroscopic study of eleven F dwarf members. Thus the cluster metallicity is relatively close to the solar value.

In the last decade there have been several attempts to determine the distance of Melotte 111. For example, using *Hipparcos* parallax measurements, Van Leeuwen (1999) and Robichon et al. (1999) have estimated $d=89.9 \pm 2.1\text{pc}$ and $d=87.0 \pm 1.6\text{pc}$, respectively. However, the reliability of both of these measurements has been challenged by Pinsonneault et al. (1998) and Makarov (2003). The former matched a theoretical isochrone to the cluster sequence in the $B\text{--}V$ colour to obtain $d=80.9 \pm 1.5\text{pc}$ or $d=84.1\text{pc}$ assuming $[\text{Fe}/\text{H}]=-0.07 \pm 0.02$ or solar metallicity respectively. The latter re-assessed the *Hipparcos* intermediate astrometry data using a method which reduced the impact of errors in the along-scan attitude parameters to determine $d=80.6 \pm 1.6\text{pc}$. However, from his new reduction of the raw *Hipparcos* data, which included an improved treatment for the along-scan attitude issues and which is claimed to be superior to the Makarov (2003) approach, van Leeuwen (2007) has determined $d=86.7^{+1.0}_{-0.9}\text{pc}$. This is consistent with the Geneva photometry based estimate of Nicolet (1981), $d=85.4 \pm 4.9\text{pc}$ and is closer to the Pinsonneault et al. (1998) determination, particularly if the cluster metallicity is nearer solar than originally assumed by these authors. As a consequence of this close proximity and the high galactic latitude of Melotte 111, levels of foreground reddening are very low e.g. $E(B - V)=0.006 \pm 0.013$, Nicolet (1981); $E(B - V) \leq 0.0032$, Taylor (2006).

The mean heliocentric radial velocity of cluster members is close to $r_v \approx 0\text{kms}^{-1}$. For example, Abt & Willmarth (1999) measured $r_v=-0.4 \pm 0.4\text{kms}^{-1}$ from sixteen stars. Kharchenko et al. (2005) determined $r_v=-1.17 \pm 0.99\text{kms}^{-1}$ by cross-referencing the

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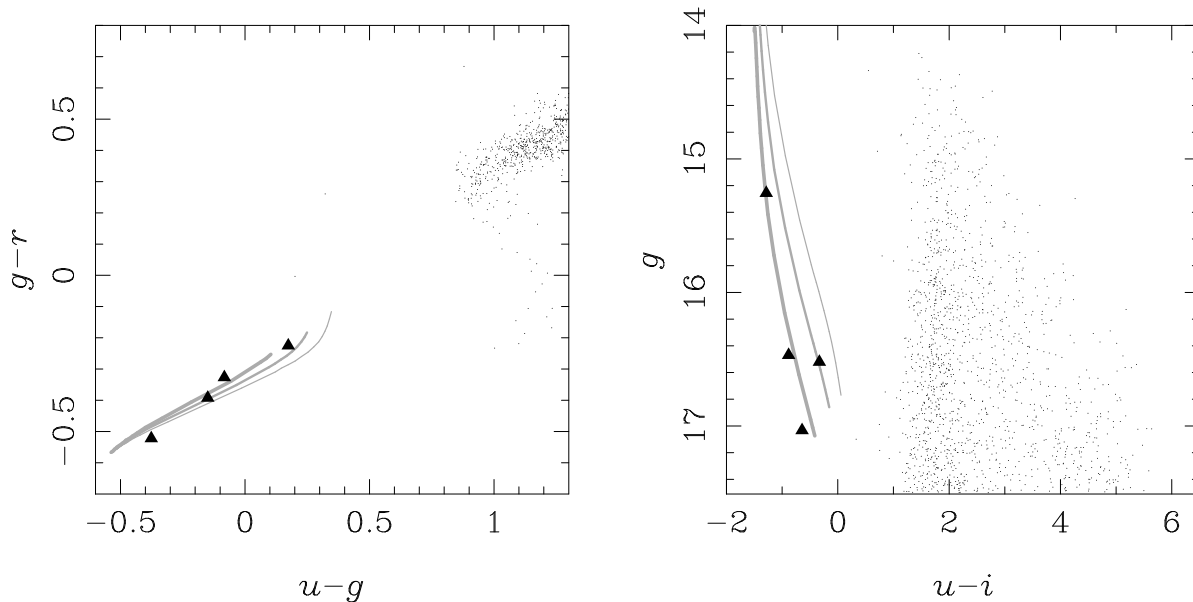


Figure 1. Left: ugr colour-colour diagram of stellar objects lying within the projected core radius of Melotte 111. Theoretical colour-colour tracks for DA white dwarfs with cooling times $\lesssim 600$ Myrs, from Holberg & Bergeron (2006), are overplotted (thin grey line, $0.7M_{\odot}$, medium grey line, $0.9M_{\odot}$, thick grey line, $1.1M_{\odot}$). Probable white dwarfs are highlighted (triangles). Right: $g,u-i$ colour-magnitude diagram of the stellar objects lying within the projected core radius of Melotte 111. Theoretical white dwarf tracks are overplotted (as previously denoted). The locations in colour-magnitude space of the four probable white dwarfs (triangles) indicate that they are potentially members of Melotte 111.

ASCC-2.5 catalogue (Kharchenko et al. 2001) with the General Catalogue of Radial Velocities (Barbier-Brossat & Figon 2000). From CORAVEL spectroscopic observations of the G7 III + A2.5IV giant binary member Trumpler 91 (Trumpler 1938), Mermilliod, Mayor & Udry (2008) estimate $v_r = +1.06 \pm 1.5 \text{ km s}^{-1}$. Despite being nearby, the tangential motion of members is rather small. From *Hipparcos* data Robichon et al. (1999) determine $\mu_{\alpha} \cos \delta = -11.38 \pm 0.23 \text{ mas yr}^{-1}$, $\mu_{\delta} = -9.05 \pm 0.12 \text{ mas yr}^{-1}$. This is corroborated by the location of the clump of stars brighter than $J=11$ seen in a UCAC2 proper motion vector point diagram for the region of sky centered on the cluster (Figure 1 of Casewell et al. 2006). Kraus & Hillenbrand (2007) have recently performed a detailed study of the structure and the mass of Melotte 111 utilising both astrometry and photometry. They have concluded that the projected tidal radius is $4.3 \pm 0.2^{\circ}$, which translates to $6.4 \pm 0.3 \text{ pc}$ at a distance of $d=85 \text{ pc}$, and that the total cluster mass is $M_{\text{tot}} = 112 \pm 16 M_{\odot}$.

To date, there have been very few efforts to identify and study the white dwarf population of Melotte 111. This is presumably because the cluster is relatively sparse and its members do not have a distinctive proper motion. From a UBV photographic survey of 21.2 sq. degrees of sky centered on the cluster down to $m_{\text{pg}} \approx 17$, Stephenson (1960) identified five candidate white dwarf members, but none of these appears to have yet been subject to detailed follow-up study. Brosch et al. (1998) used the *FAUST* ultraviolet imaging telescope to observe a 67.5 sq. degree region of sky centered on the Coma galaxy cluster ($\text{RA}=12^{\text{h}}58^{\text{m}}$, $\text{DEC}=+28^{\circ}05^{\text{m}}$, J2000.0) and claims to have unearthed ~ 5 -10 candidate white dwarf members of Melotte 111. However, these objects all lie well beyond the tidal radius of the cluster and thus are clearly not gravitationally bound members.

Nevertheless, based on scaling the number of known white dwarf members of the slightly older, more massive Hyades ($M_{\text{tot}}=300\text{-}460 M_{\odot}$, Pels et al. 1975, Reid 1992; $N_{\text{WD}} \approx 10$, von Hippel 1998) and Praesepe ($M_{\text{tot}}=500\text{-}600 M_{\odot}$, Adams et al. 2002,

Kraus & Hillenbrand 2007; $N_{\text{WD}} \approx 10$, Casewell et al. 2008) clusters, we should expect a photometric survey of Melotte 111 to unearth ~ 2 degenerate members. The detailed investigation of the white dwarf members of open star clusters (e.g. Sweeney 1976, Weidemann 1977, Weidemann 2000, Williams et al. 2004, Kalirai et al. 2005, Dobbie et al. 2006a) is arguably the best observational approach to ascertaining the form of the stellar initial mass-final mass relation (IFMR). The difference between the age of an open star cluster and the cooling time of a white dwarf member provides an estimate of the lifetime of the progenitor star. The mass of the progenitor star can then be estimated by comparing this lifetime to the predictions of stellar evolutionary calculations. Robust constraints on the form of the IFMR are very useful to several threads of astrophysical research. For example, the relation is an important component of models of the chemical evolution of the Galaxy as it provides an estimate of the amount of gas, enriched with C, N and other metals, a low or intermediate mass star returns to the ISM (e.g. Carigi, Colin & Peimbert 1999). Understanding the form of the IFMR is crucial to deciphering information locked up in the white dwarf luminosity functions of stellar populations (e.g. Jeffery et al. 2007, Oswalt et al. 1996). Furthermore, the shape of the upper end of the IFMR is of particular interest as it places limits on the minimum mass of star that will experience a core-collapse supernova explosion. With a tight handle on this mass, for example, the observed diffuse SNe neutrino background can serve as an empirical normalisation check on estimates of the star formation history of the universe (e.g. Hopkins et al. 2006).

Driven by a desire to improve current observational constraints on the form of the IFMR and the availability of high quality multiband photometry from the Sloan Digital Sky Survey (SDSS) for Melotte 111, we have undertaken a search of the central regions of the cluster for white dwarf members. In the next section we outline our photometric and astrometric survey of the cluster center. We then describe the acquisition and analysis of our spectroscopic follow-up data and the use of this to assess the membership status

Table 1. A summary of the astrometric and photometric properties of the four candidate white dwarf members of Melotte 111 unearthed by our SDSS based imaging survey of the central cluster region.

Object	Stephenson ID No.	u	g	r	i	$\mu_\alpha \cos \delta$ (mas yr ⁻¹)	μ_δ (mas yr ⁻¹)
SDSS J121635.01+262934.7	1	14.88±0.03	15.26±0.02	15.78±0.02	16.16±0.01	-29.0±10.3	-13.2±9.2
SDSS J121845.69+264831.7	2	16.32±0.01	16.47±0.01	16.86±0.02	17.20±0.03	61.2±58.8	-55.4±57.0
SDSS J121856.17+254557.1	3	16.69±0.01	16.52±0.02	16.75±0.01	17.03±0.02	-9.7±7.9	-8.2±8.2
SDSS J122420.51+264738.9	-	16.95±0.03	17.03±0.02	17.36±0.02	17.59±0.03	2.5±6.2	-10.0±6.1

of candidates. Finally, we examine a likely white dwarf member in the context of the IFMR.

2 A SEARCH FOR POTENTIAL WHITE DWARF MEMBERS OF MELOTTE 111

2.1 Optical photometry

Melotte 111 lies entirely within the footprint of the SDSS data release 6 (DR6), so for this region of sky we have at our disposal optical photometry in five bands, *ugriz*, with a precision of up to 2-3% (Adelman-McCarthy et al. 2008). Harris et al. (2003) have demonstrated that single white dwarfs with $T_{\text{eff}} \gtrsim 12000\text{K}$ are clearly separated from main sequence objects and quasars in a *ugr* colour-colour diagram. Therefore, as a first step, we have extracted from the SDSS DR6 Data Archive Server, clean *u, g* and *r* band photometry for objects classified as stellar lying within 1.5° of the cluster center. This corresponds roughly to the projected *e*-folding radius for the surface density of $0.5\text{-}1.0M_\odot$ members (Kraus & Hillenbrand 2007). We have imposed a brightness criterion of $g \leq 17.5$ since given the age and the distance of the cluster we would not expect to find white dwarf members below this magnitude limit (e.g. Bergeron et al. 1995). The *ugr* colour-colour diagram for these data is shown in Figure 1, left. Model colours (Bergeron et al. 1995, Holberg & Bergeron 2006) for 0.7, 0.9 and $1.1M_\odot$ DA white dwarfs, with $\tau_{\text{cool}} \leq 600\text{Myrs}$, are overplotted (thin grey, medium grey and thick grey line respectively). Inspection of this plot reveals that four objects clearly stand out as candidate white dwarfs (filled triangles). Nevertheless, from this analysis alone we cannot determine if these are cluster members since field white dwarfs and some hot subdwarfs can also reside in this part of colour-colour space. In an attempt to exclude field contaminants we have examined their location in the *u-i, g* colour-magnitude diagram (Figure 1, right). Once again we have overplotted synthetic photometric tracks (Bergeron et al. 1995, Holberg & Bergeron 2006) for 0.7, 0.9 and $1.1M_\odot$ DA white dwarfs with $\tau_{\text{cool}} \leq 600\text{Myrs}$, here placed at $d=85\text{pc}$ (denoted as in the colour-colour plot). However, given the effects of the finite depth of Melotte 111 ($r_{\text{tidal}}=6.4 \pm 0.3\text{pc}$) and the proximity of the four objects to these model tracks, at this stage we are led to retain all as candidate white dwarf cluster members. We note that our three brightest objects were previously identified as potential members of Melotte 111 by Stephenson (1960). The coordinates and the *ugri* photometry for all four candidates can be found in Table 1.

2.2 Proper motions

As a further aid to discriminating between cluster members and the field population, we have extracted proper motions for the four candidate white dwarfs from the SuperCOSMOS Science Archive (Table 1). These measurements, which are plotted in Figure 2,

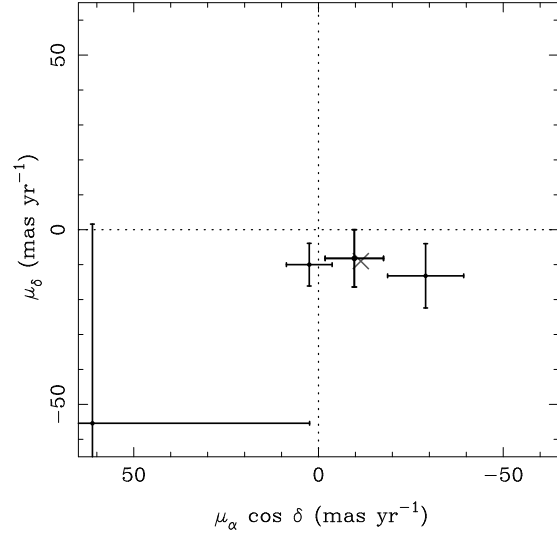


Figure 2. A proper motion vector point diagram, based on SuperCOSMOS data obtained from the Survey Science Archive, for the photometrically selected candidate white dwarf members of Melotte 111. The mean proper motion of cluster members, as determined by Robichon et al. (1999) using Hipparcos data, is highlighted ('x'). As the proper motion of SDSS J122420.51+264738.9 lies $\gtrsim 2.2\sigma$ from the cluster mean we conclude that it is likely to be a field star. The proper motions of the remaining three potential white dwarfs can be considered at least marginally consistent with Melotte 111.

have been determined with respect to background galaxies and, like the Hipparcos astrometry (e.g. Robichon et al. 1999), are effectively absolute (see Hambly et al. 2001 for further details). Although the small proper motion of the cluster dictates that these SuperCOSMOS data are not of sufficient accuracy to compellingly demonstrate that a particular candidate is an associate of Melotte 111, an object must have astrometric properties at least consistent with the cluster to be considered a member. Indeed, since SDSS J122420.51+264738.9 has a proper motion lying $\gtrsim 2.2\sigma$ from the Hipparcos determination of the cluster mean ('x' in Figure 2) we conclude that it is likely to be a field star and consequently do not consider it further in our analysis. While SDSS J121856.17+254557.1 is the only candidate with a proper motion within 1σ of that of Melotte 111, the measurements for SDSS J121635.01+262934.7 and SDSS J121845.69+264831.7 are at least marginally consistent with that of the cluster and do not rule out the possibility that either is a member. However, a recent spectroscopic analysis of SDSS J121635.01+262934.7 (PG1214+268) has confirmed it to be a DA white dwarf with $M \approx 0.6M_\odot$ and $T_{\text{eff}} \approx 65000\text{K}$, residing at $d \approx 315\text{pc}$ (Liebert, Bergeron & Holberg 2005). Thus we can say with confidence that it is not a member of Melotte 111 and exclude it from further discussion. Clearly, spec-

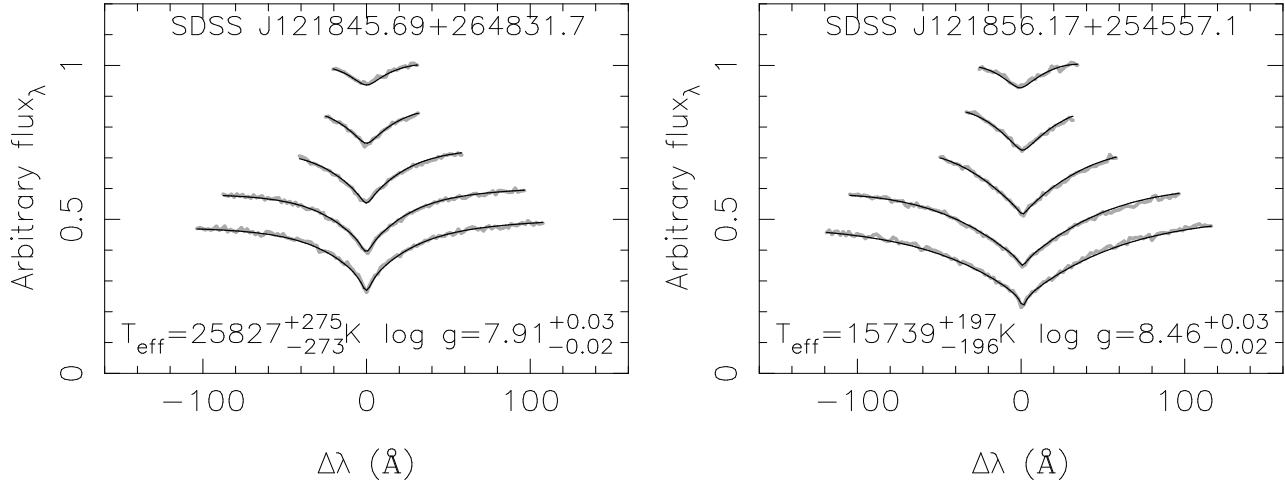


Figure 3. The results of fitting synthetic profiles (thin black lines) to the observed Balmer lines, H- β to H-8 (thick grey lines). The flux $_{\lambda}$ units are arbitrary.

troscopic data is required to examine more thoroughly the nature and the membership status of our two remaining candidates.

3 SPECTROSCOPIC FOLLOW-UP OF SDSS J121845.69+264831.7 AND SDSS J121856.17+254557.1

3.1 The WHT observations

We have obtained optical spectroscopy of both SDSS J121845.69+264831.7 and SDSS J121856.17+254557.1 using the William Herschel Telescope (WHT) and the double-armed Intermediate dispersion Spectrograph and Imaging System (ISIS). These observations were conducted on 2006/02/02 and 2008/07/25, when excellent conditions prevailed. On both nights the sky was very clear with seeing ~ 0.6 – $0.9''$, while additionally on 2008/07/25, humidity levels were very low ($\sim 10\%$). For the observation of SDSS J121845.69+264831.7, ISIS was configured with a $1.0''$ slit and data covering $\lambda \approx 3600$ – 5500\AA were acquired using the R300B grating on the blue arm only ($\lambda/\delta\lambda \approx 1200$). For the observation of SDSS J121856.17+254557.1, the spectrograph was configured with a $0.6''$ slit and data covering the two wavelength ranges, $\lambda \approx 3600$ – 5500\AA , 6200 – 7000\AA , were obtained simultaneously using the R300B ($\lambda/\delta\lambda \approx 2000$) and R1200R ($\lambda/\delta\lambda \approx 10000$) gratings on the blue and red arms respectively. We performed a series of short integrations to obtain total exposure times of 20 and 45 minutes on SDSS J121845.69+264831.7 and SDSS J121856.17+254557.1 respectively. The CCD frames were debiased and flat fielded using the IRAF procedure CCDPROC. Cosmic ray hits were removed using the routine LACOS SPEC (van Dokkum 2001). Subsequently, the spectra were extracted using the APEXTRACT package and wavelength calibrated by comparison with the CuAr+CuNe arc spectra taken immediately before and/or after the science exposures. The removal of remaining instrument signature from the science spectra obtained on the first night was undertaken using an observed and a synthetic spectrum (Bohlin 2000) of G191-B2B. Data obtained on the second night were corrected using an observation of the bright DC white dwarf WD1918+386. The reduced spectra clearly show both objects to be hydrogen rich white dwarfs, ie. WD1216+270 and WD1216+260.

3.2 The model atmosphere calculations

We have used recent versions of the plane-parallel, hydrostatic, non-local thermodynamic equilibrium (non-LTE) atmosphere and spectral synthesis codes TLUSTY (v200; Hubeny 1988, Hubeny & Lanz 1995) and SYNPEC (v48; Hubeny, I. and Lanz, T. 2001, <http://nova.astro.umd.edu/>) to generate a grid of pure-H synthetic spectra covering the effective temperature and surface gravity ranges $T_{\text{eff}} = 15000$ – 30000K and $\log g = 7.5$ – 8.75 respectively. We have employed a model H atom incorporating the 8 lowest energy levels and one superlevel extending from $n=9$ to $n=80$, where the dissolution of the high lying levels was treated by means of the occupation probability formalism of Hummer & Mihalas (1988), generalised to the non-LTE situation by Hubeny, Hummer & Lanz (1994). The calculations assumed radiative equilibrium (since our test calculations and those of the referee, Detlev Koester, indicate that in this effective temperature regime convection transports $\lesssim 1\%$ of the flux and its neglect has a negligible impact on the emergent spectrum) and included the bound-free and free-free opacities of the H^- ion and incorporated a full treatment for the blanketing effects of HI lines and the Lyman $-\alpha$, $-\beta$ and $-\gamma$ satellite opacities as computed by N. Allard (e.g. Allard et al. 2004). During the calculation of the model structure the hydrogen line broadening was addressed in the following manner: the broadening by heavy perturbers (protons and hydrogen atoms) and electrons was treated using Allard's data (including the quasi-molecular opacity) and an approximate Stark profile (Hubeny, Hummer & Lanz 1994) respectively. In the spectral synthesis step detailed profiles for the Balmer lines were calculated from the Stark broadening tables of Lemke (1997).

3.3 Determination of the effective temperature and surface gravity

As in our previous work (e.g. Dobbie et al. 2006a), comparison between the models and the low resolution data is undertaken using the spectral fitting program XSPEC (Shafer et al. 1991). In our analysis all lines from H- β to H-8 are included in the fitting process. XSPEC works by folding a model through the instrument response before comparing the result to the data by means of a χ^2 -statistic. The best fit model representation of the data is found by increment-

Table 2. Alternative designations, effective temperatures, surface gravities, predicted absolute g magnitudes and distance moduli for SDSS J121845.69+264831.7 and SDSS J121856.17+254557.1.

Object	Other IDs	T_{eff}^*	$\log g^*$	M_g	$(m-M)_g$
SDSS J121845.69+264831.7	LB4, WD1216+270	25827^{+275}_{-273}	$7.91^{+0.03}_{-0.02}$	$9.94^{+0.11}_{-0.12}$	$6.53^{+0.12}_{-0.11}$
SDSS J121856.17+254557.1	Ton 607, CSI+26-12165, WD1216+260	15739^{+197}_{-196}	$8.46^{+0.03}_{-0.02}$	$11.84^{+0.12}_{-0.12}$	$4.68^{+0.12}_{-0.12}$

* Formal fit errors.

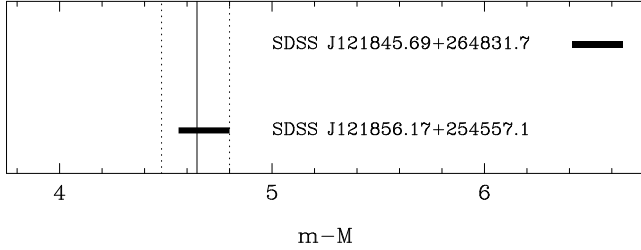


Figure 4. The estimated distance moduli of WD1216+270 (SDSS J121845.69+264831.7) and WD1216+260 (SDSS J121856.17+254557.1) based on the observed SDSS photometry and the synthetic photometry from Holberg & Bergeron (2006). The distance of the centre ($d=85\text{pc}$) and the tidal limits ($r_{\text{tidal}}=6.4\text{pc}$) of the cluster are overplotted (solid and dotted vertical lines respectively). WD1216+260 resides within the tidal bounds of Melotte 111.

ing free grid parameters in small steps, linearly interpolating between points in the grid, until the value of χ^2 is minimised. Errors in the T_{eff} s and $\log g$ s are calculated by stepping the parameter in question away from its optimum value and re-determining minimum χ^2 until the difference between this and the true minimum χ^2 corresponds to 1σ for a given number of free model parameters (e.g. Lampton et al. 1976). The results of our fitting procedure are given in Table 2 and shown overplotted on the data in Figure 3. It should be noted that the parameter errors quoted here are formal 1σ fit errors and undoubtedly underestimate the true uncertainties. For our subsequent calculations we adopt more realistic levels of uncertainty of 2.3% and 0.07dex in effective temperature and surface gravity respectively (e.g. Napiwotzki, Green & Saffer 1999).

3.4 Distance, radial velocity and cluster membership status

Using the effective temperature and the surface gravity estimates listed in Table 2, and the model white dwarf photometry of Bergeron et al. (1995), which has been updated by Holberg & Bergeron (2006), we have derived the absolute g magnitudes (M_g) of WD1216+270 (SDSS J121845.69+264831.7) and WD1216+260 (SDSS J121856.17+254557.1). Subsequently, we have determined the distance moduli of these two objects, neglecting extinction which is minimal along this line of sight. These are plotted in Figure 4 (solid bars), along with reasonable estimates for the distance and the tidal bounds of Melotte 111 ($d=85\text{pc}$, $r_{\text{tidal}}=6.4\text{pc}$). Inspection of this plot reveals that while WD1216+270 is probably a field star residing some way behind the cluster, the distance modulus of WD1216+260 argues rather strongly that it is associated with Melotte 111.

To further scrutinise the membership status of this one remaining candidate (WD1216+260), we have acquired a radial velocity measurement. We have removed the effects of telluric water vapour from the red arm ISIS spectroscopic data using a template absorption spectrum. Custom written IDL routines have been used to nor-

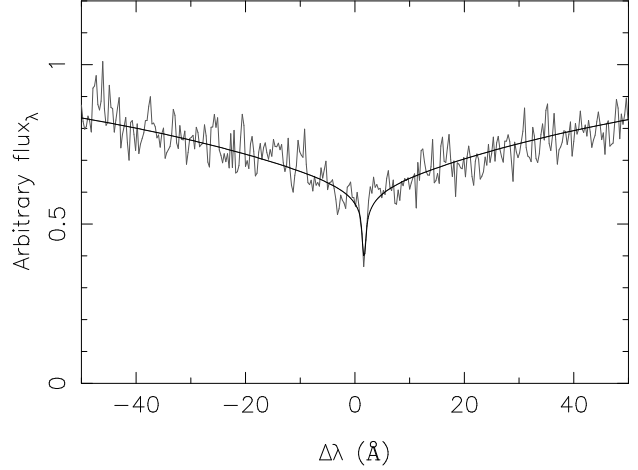


Figure 5. The results of our fitting of a synthetic profile (thin black line) to the central portions of the observed H- α Balmer line of WD1216+260 (thick grey lines). The flux $_{\lambda}$ units are arbitrary.

malise both the observed H- α line and the profile from a synthetic spectrum corresponding to $T_{\text{eff}}=15750\text{K}$ and $\log g=8.45$. Subsequently, the model has then been compared to the data, where the Levenberg-Marquardt algorithm has been used to minimise a χ^2 fit statistic. The result of this process is displayed in Figure 5. The line velocity shift, after correction to the heliocentric rest frame, is shown in Table 3. The uncertainty in this measurement has been estimated using the bootstrapping method of statistical resampling (Efron 1982). The gravitational redshift component of the velocity shift was then determined using Equation 1, where M and R are the mass and radius of the white dwarf in solar units respectively and v is the gravitational redshift in kms^{-1} .

$$v = 0.635M/R \quad (1)$$

The mass and radius have been determined using modern evolutionary tracks supplied by the Montreal group (e.g. Fontaine, Brassard & Bergeron 2001), more specifically the calculations which assume a mixed CO core and thick H surface layer structure. The radial velocity is represented by the difference between the measured shift of the line and the calculated gravitational redshift. It can be seen from Table 3 that the radial velocity of WD1216+260 is very close to the value expected for a member of Melotte 111 and entirely consistent within the measurement uncertainties. On the basis of the projected location, the proper motion, the distance and the radial velocity of WD1216+260, we conclude that it is a white dwarf member of Melotte 111.

Table 3. Additional physical details of WD1216+260 (SDSS J121856.17+254557.1), the white dwarf probable member of Melotte 111. The mass and the cooling time have been estimated using the mixed CO core composition “thick H-layer” evolutionary calculations of the Montreal Group (e.g. Fontaine, Brassard & Bergeron 2001).

Object	M_{WD} (M_{\odot})	R_{WD} ($R_{\odot} \times 10^{-3}$)	rv_{Mel111}	H- α shift (km s^{-1})	GR	rv_{WD}	τ_c (Myrs)	M_{init} (M_{\odot})
SDSS J121856.17+254557.1	0.902 ± 0.045	9.26 ± 0.84	-0.4 ± 0.4	$57.1^{+0.5}_{-2.5}$	61.9 ± 6.4	$-4.8^{+6.4}_{-6.9}$	363^{+46}_{-41}	$4.77^{+5.37}_{-0.97}$

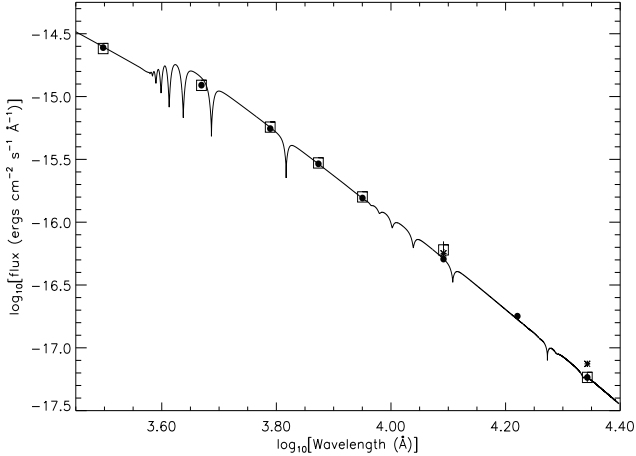


Figure 6. The observed optical (SDSS u, g, r, i and z) to near-IR (2MASS PSC J and UKIDSS GCS K) spectral energy distribution of WD1216+260 (open squares and error bars). The model photometry of Bergeron et al. (1995) as updated by Holberg & Bergeron (2006) is overplotted (solid circles), where we have assumed $T_{\text{eff}}=15739\text{K}$ and $\log g = 8.46$ and a distance modulus of $(m-M)_g=4.68$. A TLUSTY/SYNPEC synthetic spectrum for $T_{\text{eff}}=15739\text{K}$ and $\log g = 8.46$ and scaled to match the observed optical photometry, is also overplotted (solid line). The estimated J and K flux levels resulting from the presense of a putative spatially unresolved $M=0.036M_{\odot}$ brown dwarf companion are shown (asterisks).

4 A WHITE DWARF MEMBER OF MELOTTE 111

4.1 The near-IR energy distribution of WD1216+260

We note that due to its proximity and intrinsic luminosity WD1216+260 was detected in the 2MASS All Sky Survey (Skrutskie et al. 2006), albeit weakly and only in the shortest waveband, J . It is listed in the Point Source Catalogue as having $J_{2\text{MASS}}=16.79 \pm 0.17$. Furthermore, it was detected at K in the course of the Galactic Clusters Survey (GCS) component of the United Kingdom Infrared Digital Sky Survey (UKIDSS; Lawrence et al. 2007). Data extracted from the Wide Field Camera Science Archive (WSA; Hambly et al. 2008) indicates that for this object, $K_{\text{WFCAM}}=17.08 \pm 0.09$. UKIDSS J and H band photometry are not yet available for the Melotte 111 region of sky.

We have used data listed in Holberg & Bergeron (2006; SDSS $ugriz$), Cohen et al (2003; 2MASS J) and Hewett et al (2006; WFCAM K) to convert the optical and near-IR magnitudes to fluxes and have plotted these in Figure 6 (open squares). Model DA white dwarf photometry, from Bergeron et al. (1995) as updated by Holberg & Bergeron (2006), is overplotted (solid circles), where we have assumed $T_{\text{eff}}=15739\text{K}$ and $\log g = 8.46$ and a distance modulus of $(m-M)_g=4.68$. Note that the model K magnitude has been moved from the 2MASS system to the Wide Field Camera (WFCAM) system using transform equations from Hodgkin et al.

(2009), here extrapolated slightly to the blue. Additionally we have overplotted a TLUSTY/SYNPEC synthetic spectrum of the appropriate effective temperature and surface gravity, which has been scaled to match the observed optical fluxes (solid line).

Approximately 25% of DAs in the effective temperature regime occupied by WD1216+260 are metal-rich (ie. DAZs; Zuckerman et al. 2003) and at least 14% of these are observed, through the existence of an infrared excess (e.g. Kilic et al. 2005, Becklin et al. 2005), to harbour a dust disk which may be associated with a former planetary system (Kilic & Redfield 2007; DAZd). The discovery of a DAZd in an open cluster, where the population age and progenitor mass can be relatively well constrained, would be of particular interest. However, the good agreement between the observed and the theoretical infrared fluxes means that the current data provide no evidence for the existence of a dust disk around WD1216+260. Moreover, these data do not indicate the presense of a close (spatially unresolved) cool low mass companion (e.g. Farihi & Christopher 2004, Dobbie et al. 2005, Maxted et al. 2006, Burleigh et al. 2006).

Since WD1216+260 is a comparatively massive object with a likely total age of $\tau \sim 500\text{Myrs}$, we are able to set a fairly tight upper limit on the mass of a putative cool companion. To do this we first moved the mean CIT magnitudes for L and T dwarfs listed in Table 9 of Vrba et al. (2004) onto the 2MASS (J) and Mauna Kea Observatories (K ; MKO) systems using published fits relating spectral type and magnitude offsets between photometric systems (Stephens & Leggett 2004). We assumed here that $K_{\text{MKO}} \approx K_{\text{WFCAM}}$, since WFCAM employs the MKO filter set (e.g. Hewett et al. 2006) and Leggett et al. (2006) find no compelling evidence for a colour term at K between the UFTI MKO system (e.g. Hawarden et al. 2001) and the WFCAM system (although their data is rather limited). We then constructed the relations, spectral type versus luminosity, effective temperature and near-IR magnitudes using the Vrba et al. (2004) data, where the COND03 models of Baraffe et al. (2003) were used to estimate the upwards offset in luminosity between this field dwarf dominated sample and the younger open cluster population. As we were aiming to set an upper limit on the mass of a putative companion, we assumed $\tau=600\text{Myrs}$ for Melotte 111 (the upper bound of the age estimate) and further offset the predicted magnitudes by $+0.4$ to account for the dispersion observed in the near-IR photometry of L/T dwarfs of a given spectral type (e.g. Tinney et al. 2003). Subsequently, beginning with T8 we combined progressively earlier and earlier spectral types with the model white dwarf photometry until the predicted flux at K matched the 3σ upper limit on the observed flux ($K_{\text{WFCAM}}=16.81$). This occurred at spectral type T2.5 ($T_{\text{eff}} \sim 1400\text{K}$), which for our adopted age corresponds to $M=0.036M_{\odot}$.

Additionally, we inspected a $1' \times 1'$ (representing a projected area of $5000\text{AU} \times 5000\text{AU}$) WFCAM K band thumbnail image centered on WD1216+260. We found that this white dwarf is the only significant detection within this region. Photometry for other catalogued point sources within $30'$ indicate that a $\geq 3\sigma$ detec-

tion corresponds to $K \lesssim 18.65$. At the distance of Melotte 111 and $\tau = 600$ Myrs this is consistent with $M \gtrsim 0.034 M_{\odot}$. Thus we conclude that WD1216+260 has no spatially resolved cool companion with $M \gtrsim 0.034 M_{\odot}$ within $a \sim 2500$ AU and no spatially unresolved cool companion with $M \gtrsim 0.036 M_{\odot}$. Farihi, Becklin & Zuckermann (2005) estimated that $\lesssim 0.5\%$ of white dwarfs have brown dwarf companions with $M \gtrsim 0.02 - 0.05 M_{\odot}$ within $a \lesssim 5000$ AU. Thus, this result is not entirely unexpected.

4.2 In the context of the IFMR

As a member of an open star cluster and having probably evolved essentially as a single star, WD1216+260 is potentially useful for constraining the form of the IFMR. Therefore, we have used the Montreal group evolutionary tracks to determine a cooling time, where cubic splines have been used to interpolate between points in this grid. The results of this process are shown in Table 3. The lifetime of the progenitor star has been derived by subtracting this cooling time from the adopted cluster age, where, for the reasons outlined in the Section 1, it has been assumed that $\tau = 500 \pm 100$ Myrs. Subsequently, we have used cubic splines to interpolate between the lifetimes calculated for stars of solar composition by Girardi et al. (2000) and have constrained the progenitor mass to the value shown in the final column of Table 3. The error we quote in the progenitor mass takes into account the spread in recent cluster age determinations and the uncertainty in the cooling time of the white dwarf, but should be regarded as an illustrative rather than a robust estimate.

We find the location of WD1216+260 in initial mass-final mass space to be consistent with the general trend outlined by the bulk of white dwarf members of near solar metallicity (ie. $-0.15 \lesssim [\text{Fe}/\text{H}] \lesssim +0.15$) open clusters (e.g. Kalirai et al. 2008 - NGC6819 and NGC7789, Claver et al. 2001 - Hyades and Praesepe, Casewell et al. 2009 - Praesepe, Kalirai et al. 2005 - NGC2099, Williams & Bolte 2007 - NGC6633, Rubin et al. 2008 - NGC1039, Dobbie et al. 2009 - NGC2287 and NGC3532, Koester & Reimers 1996 - NGC2516 and Dobbie et al. 2006a,b - Pleiades). While the mass range for the progenitor star of WD1216+260 is broad, primarily due to the substantial uncertainty on the age of Melotte 111 (e.g. Salaris et al. 2008), the most probable initial and final masses are very similar to those of the two white dwarf members of NGC2287 and the most massive degenerate in NGC1039. Therefore, WD1216+260 lends some support, albeit rather weak given the large uncertainties, to our conclusion in Dobbie et al. (2009) that the cluster data appear indicate that the IFMR is less steep at $M_{\text{init}} > 4 M_{\odot}$ than in the range $3 M_{\odot} \lesssim M_{\text{init}} \lesssim 4 M_{\odot}$. As discussed at length in Dobbie et al. (2009), this decrease in the gradient of the IFMR is expected on theoretical grounds. The form of the initial mass versus the core mass at the time of the first thermal pulse relation (Karakas, Lattanzio & Pols 2002) and a recent theoretical IFMR (Marigo & Girardi 2007), reasonably reproduce that of the data at $M_{\text{init}} > 3 M_{\odot}$, although admittedly with offsets in final mass. Additional and/or better data in the initial mass regime $M_{\text{init}} \gtrsim 5 M_{\odot}$ would help to consolidate this conclusion.

5 SUMMARY

We have utilised SDSS photometry, SuperCOSMOS proper motions and optical spectroscopy to search for white dwarf members within the central regions of the open cluster Melotte 111. We have identified one probable degenerate member, WD1216+260,

with a mass of $M_{\text{WD}} = 0.90 \pm 0.04 M_{\odot}$. The optical to near-IR energy distribution of this object, as described by SDSS, 2MASS and UKIDSS GCS data, is entirely consistent with that of an isolated DA white dwarf. We have set tight upper limits on the mass of a putative low mass companion, $M \gtrsim 0.036 M_{\odot}$ (spatially unresolved) and $M \gtrsim 0.034 M_{\odot}$, (spatially resolved and $a \lesssim 2500$ AU). Moreover, for an adopted cluster age of $\tau = 500 \pm 100$ Myrs, we have inferred the mass of its progenitor star to be $M_{\text{init}} = 4.77^{+5.37}_{-0.97} M_{\odot}$. The location of WD1216+260 in initial mass-final mass space is consistent with a near-monotonic positive correlation outlined by the bulk of open cluster white dwarfs and our earlier conclusion that the these objects appear to indicate that the IFMR is less steep at $M_{\text{init}} > 4 M_{\odot}$ than in the range $3 M_{\odot} \lesssim M_{\text{init}} \lesssim 4 M_{\odot}$, at least for metallicity close to the solar value.

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